

# Understanding Distance Uncertainties Using PDV on Dynamic Experiments



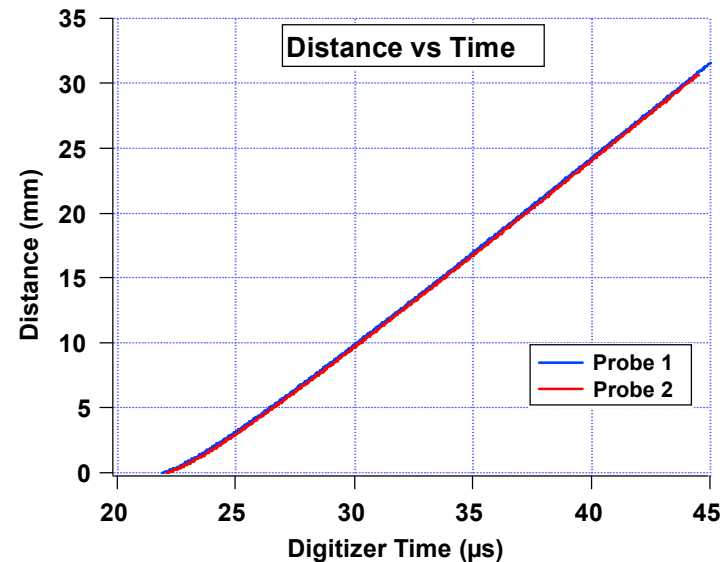
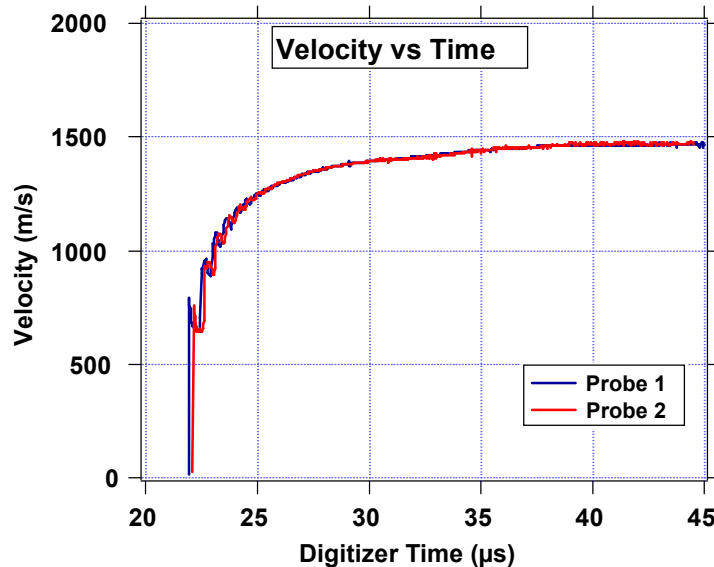
Presented to:  
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Ted Strand  
Lawrence Livermore National Laboratory

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# How accurately can we measure distance with PDV on a dynamic experiment?



Integrate the velocity to get the distance:

$$d = \int v dt$$

Some designers  
want the  
distance uncertainty  
to be  $< 10 \mu\text{m}$

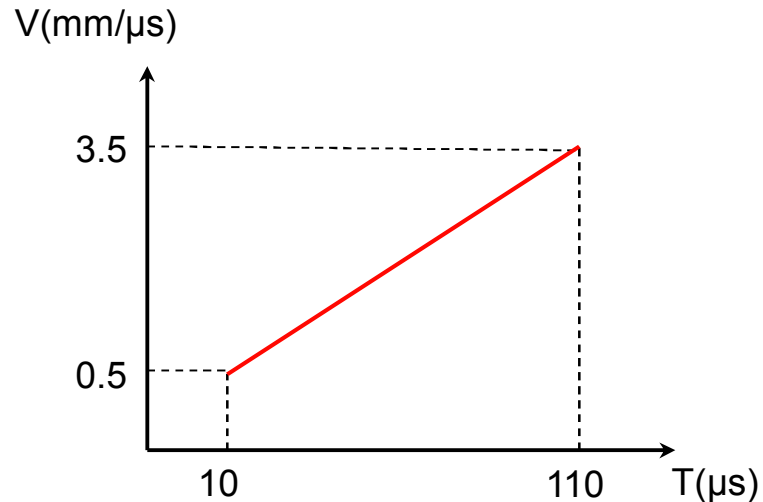
Uncertainties may accumulate with increasing distance integral.

We will examine the distance uncertainty versus various parameters in the PDV system



Run#	Wavelength				Signal:Noise				Digitizer		FT Window				Phase				Acceleration			
	1550.0	1550.1	1550.2	1550.5	1:0	1:1	1:5	1:10	0 ppm	10 ppm	256	512	1024	2048	0	1/4	1/2	3/4	1	2	3	4
01	X				X				X				X		X					X		
02		X			X				X				X		X					X		
03			X		X				X				X		X					X		
04				X	X				X				X		X					X		
05	X					X			X				X		X					X		
06	X						X		X				X		X					X		
07	X							X	X				X		X					X		
08	X				X					X			X		X					X		
09	X				X				X		X				X					X		
10	X				X				X			X			X					X		
11	X				X				X					X	X					X		
12	X				X				X				X			X				X		
13	X				X				X				X				X			X		
14	X				X				X				X					X		X		
15	X				X				X				X		X				X			
16	X				X				X				X		X						X	
17	X				X				X				X		X							X

# Build a velocity profile that corresponds to an interesting range of velocities and times



Calculate the analytic coefficients for velocity and distance

$$v = mt + b$$

$$v = 0.03t + 0.2$$

$$d = \frac{1}{2}mt^2 + bt + c$$

$$d = 0.015t^2 + 0.2t - 3.5$$

Area under trapezoid =  $\frac{1}{2} (h_1 + h_2) * b$

$$A = 0.5 * (0.5 + 3.5) * (100-10)$$

$$A = \text{distance} = 200 \text{ mm}$$

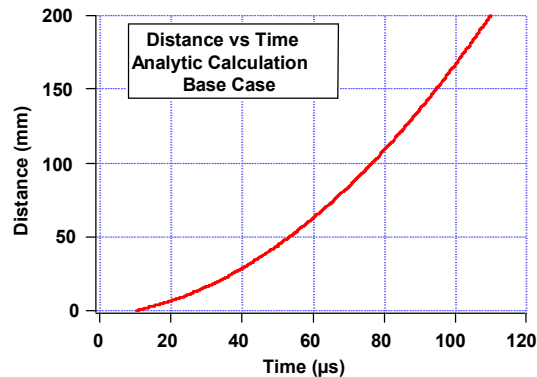
Note: 200 mm corresponds to 258065 beat cycles.

# Construct the base case beat amplitude from the analytic distance profile



Note: 50 ps/pt = 2.2 Mpts/file

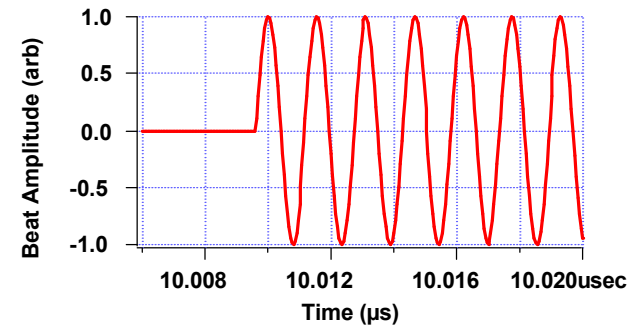
$$d = 0.015t^2 + 0.2t - 3.5$$



This is my “known” distance profile



This is my base case beat waveform



“Base Case” means:

Wavelength = 1550 nm

Noise = 0

Digitizer Sample Time = 50 ps

FT window = 1024 points

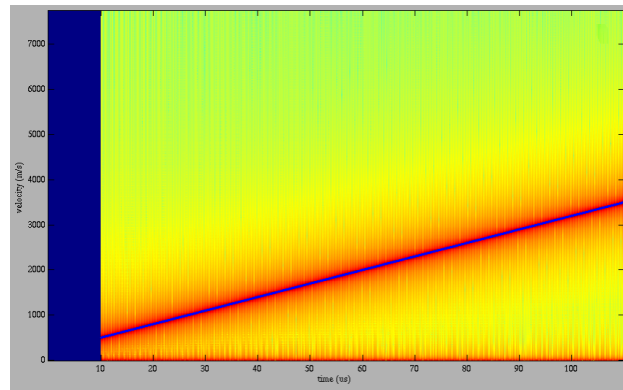
Phase = 0

Acceleration = 0.03

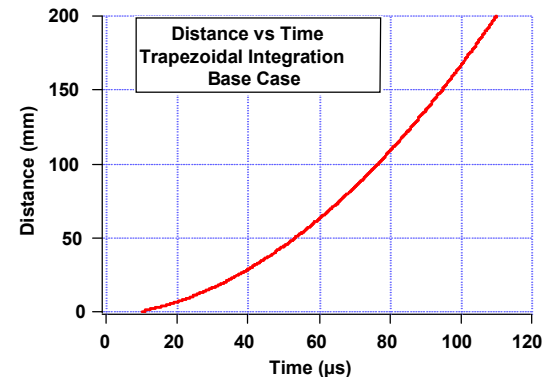
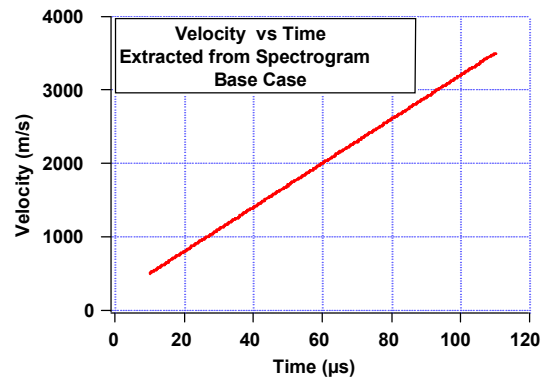
# Calculate the spectrograms, extract the velocity profile, integrate to give distance profile



Base case: laser is known = 1550nm, digitizer sample period is known = 50ps, no electrical noise in beat waveform, process spectrogram with 51.2 ns FT windows



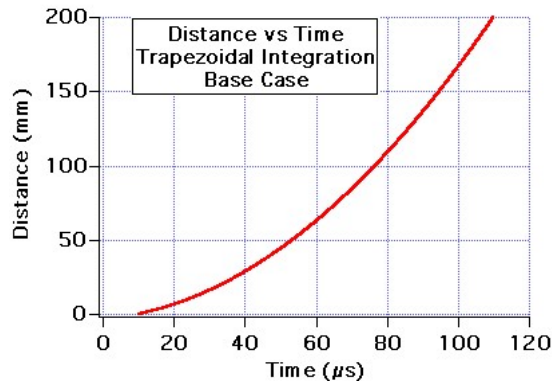
This code is described in  
“Data Analysis Using  
the FT Method”,  
Bill Kuhl, 1st Annual  
PDV Workshop.



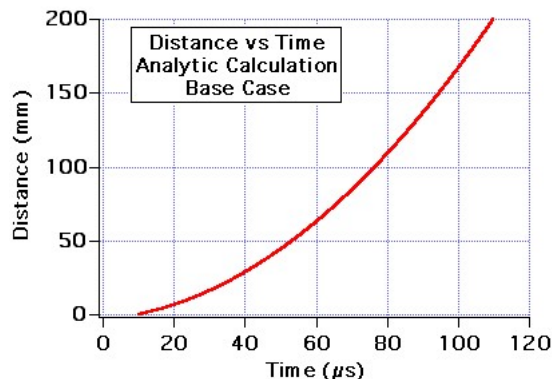
Subtract the trapezoidal integration minus the analytic calculation to get the distance error



trapezoidal integration



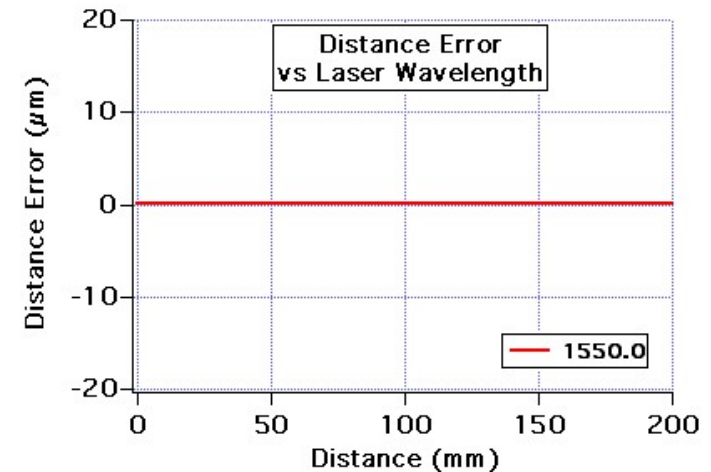
analytic calculation



subtract  
to get



Happily, the Base Case  
shows very little error.



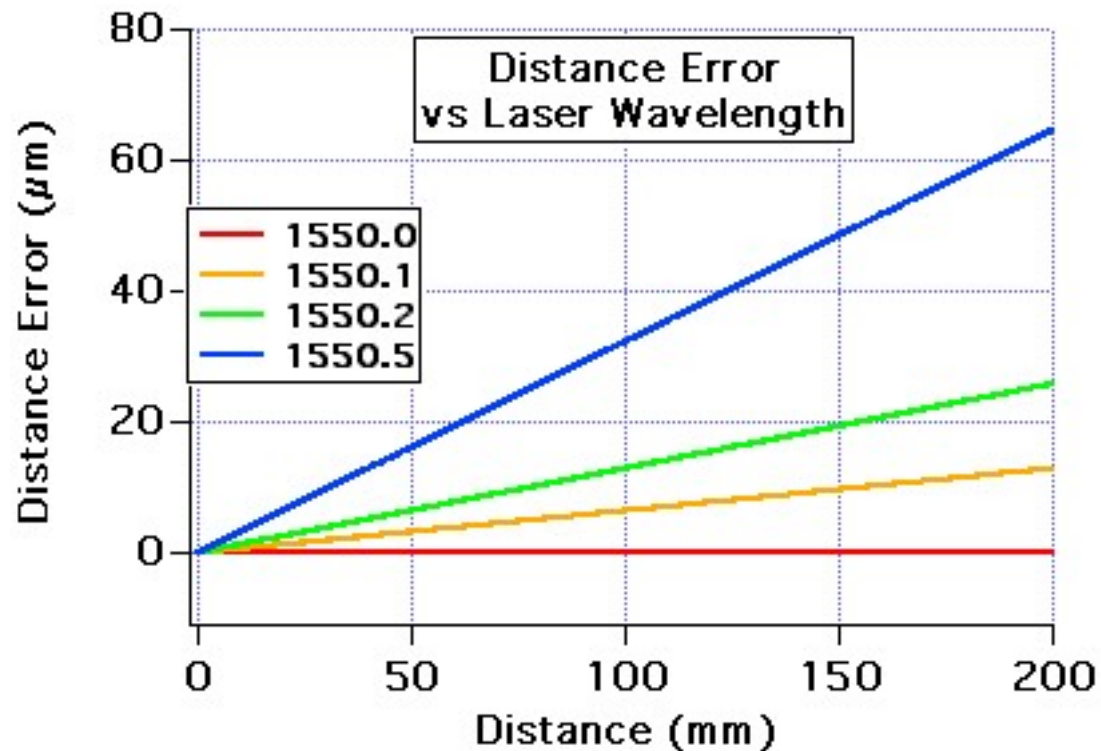
Note: x-axis is distance

Now, let's look at the  
parameter studies-->

# Study the Distance Uncertainty vs Laser Wavelength Uncertainty



Result: 0.1 nm uncertainty = 17  $\mu\text{m}$  over 200 mm

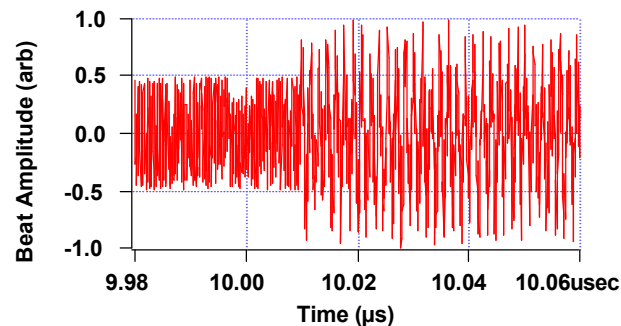
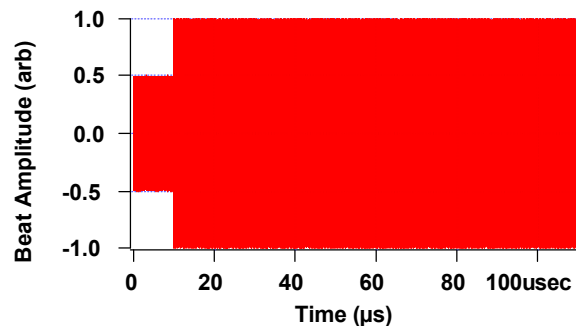


Our lasers have the following wavelengths:

1549.6  
1549.8  
1550.15  
1550.15  
1549.88  
1550.10

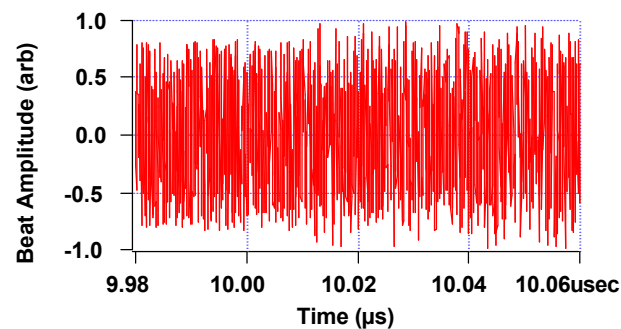
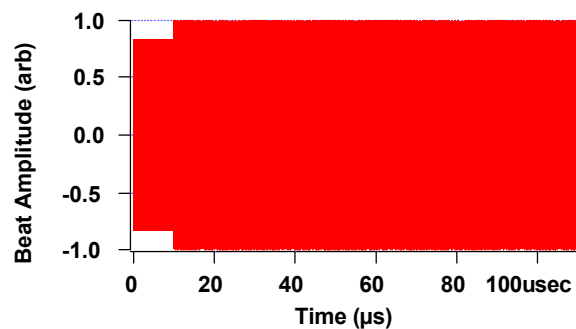


# Study the Distance Uncertainty vs Random Noise on the Beat Waveform

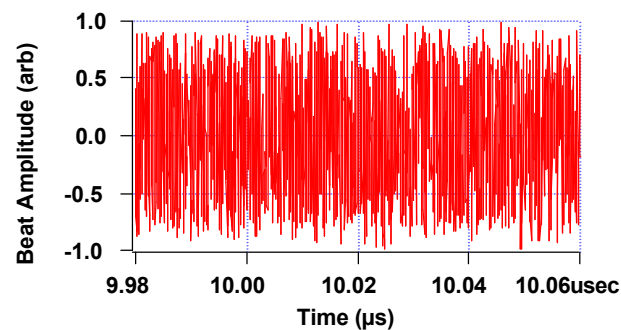
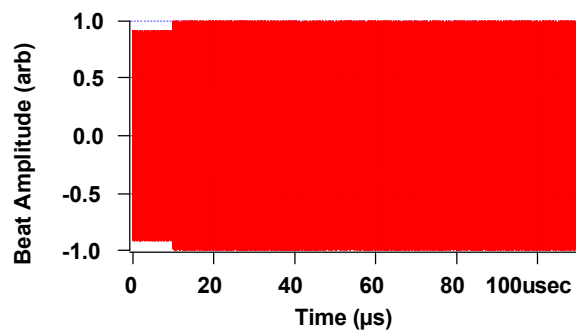


Signal:Noise

1:1



1:5

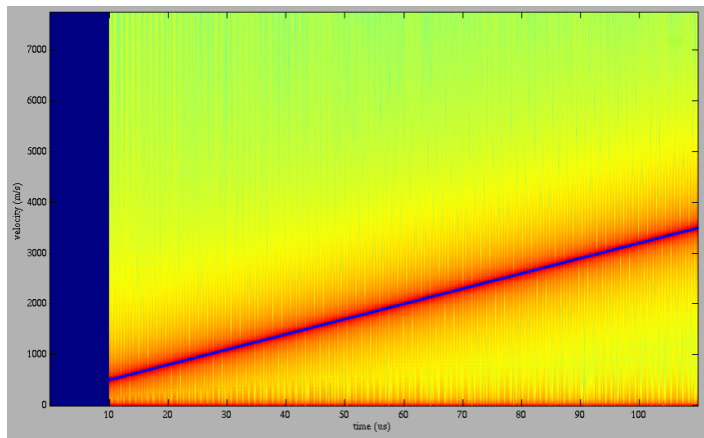


1:10

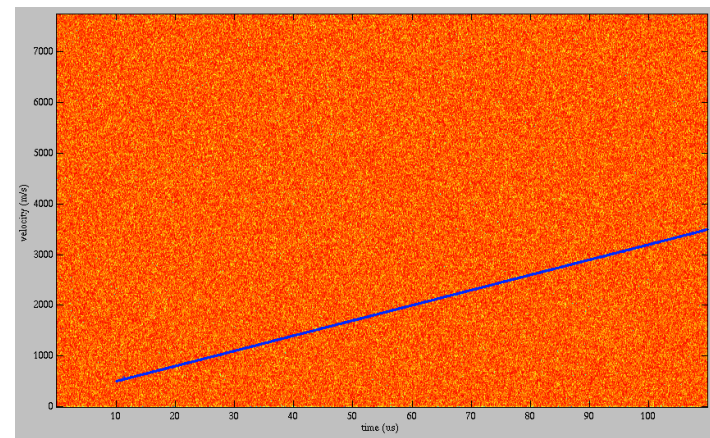
The spectrograms contain more noise  
with increasing noise on the beat waveforms



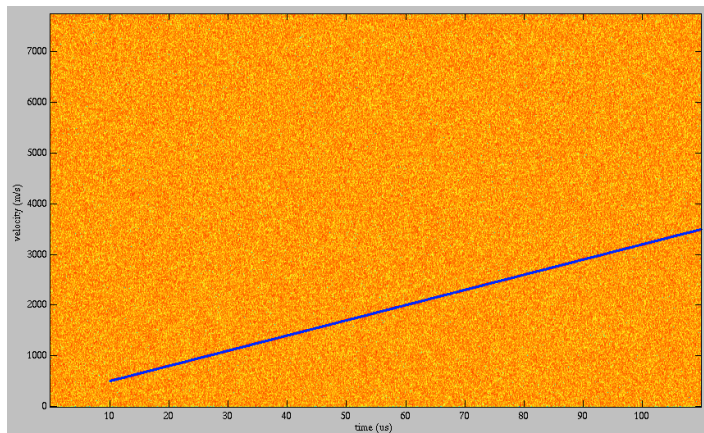
$S/N = 1:0$



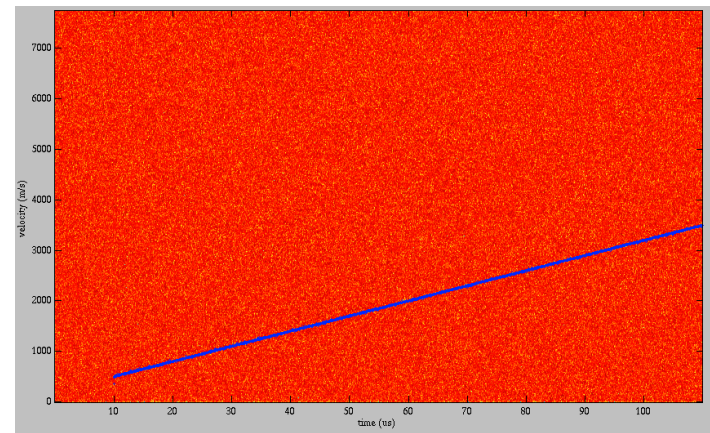
$S/N = 1:5$



$S/N = 1:1$



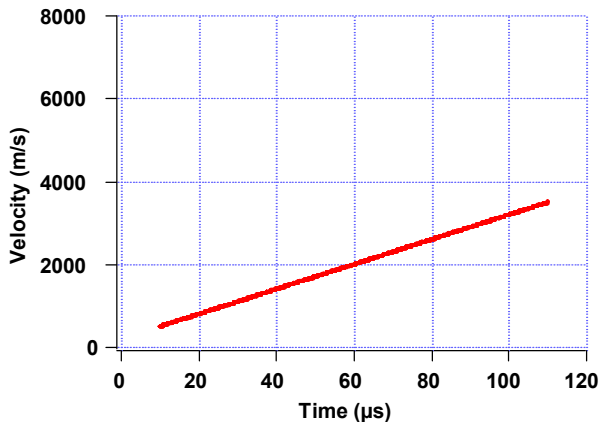
$S/N = 1:10$



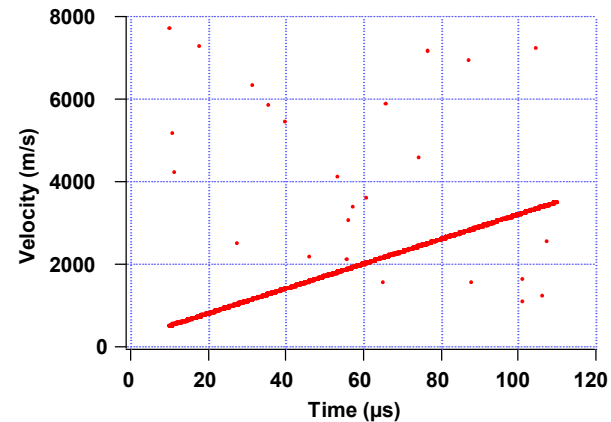
The spectrograms contain more noise  
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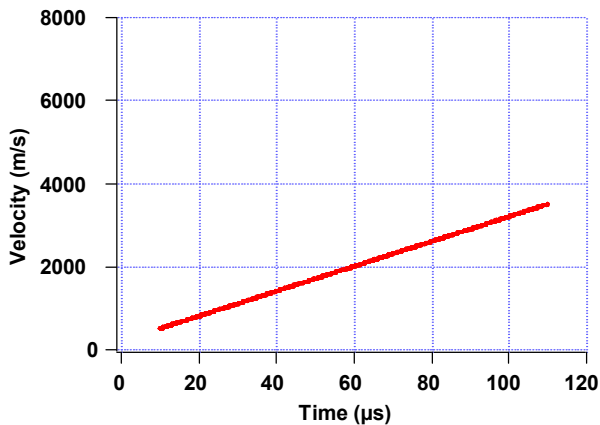
S/N = 1:0



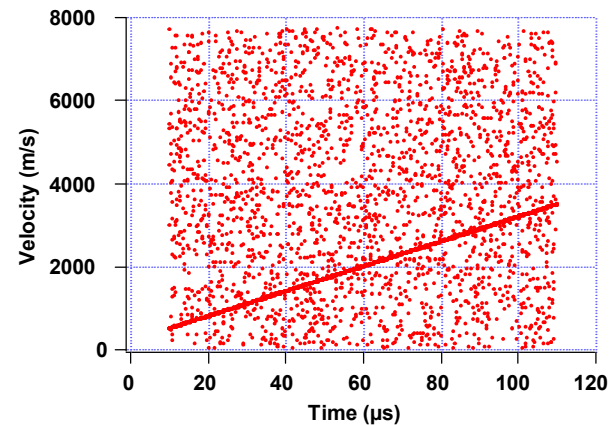
S/N = 1:5



S/N = 1:1



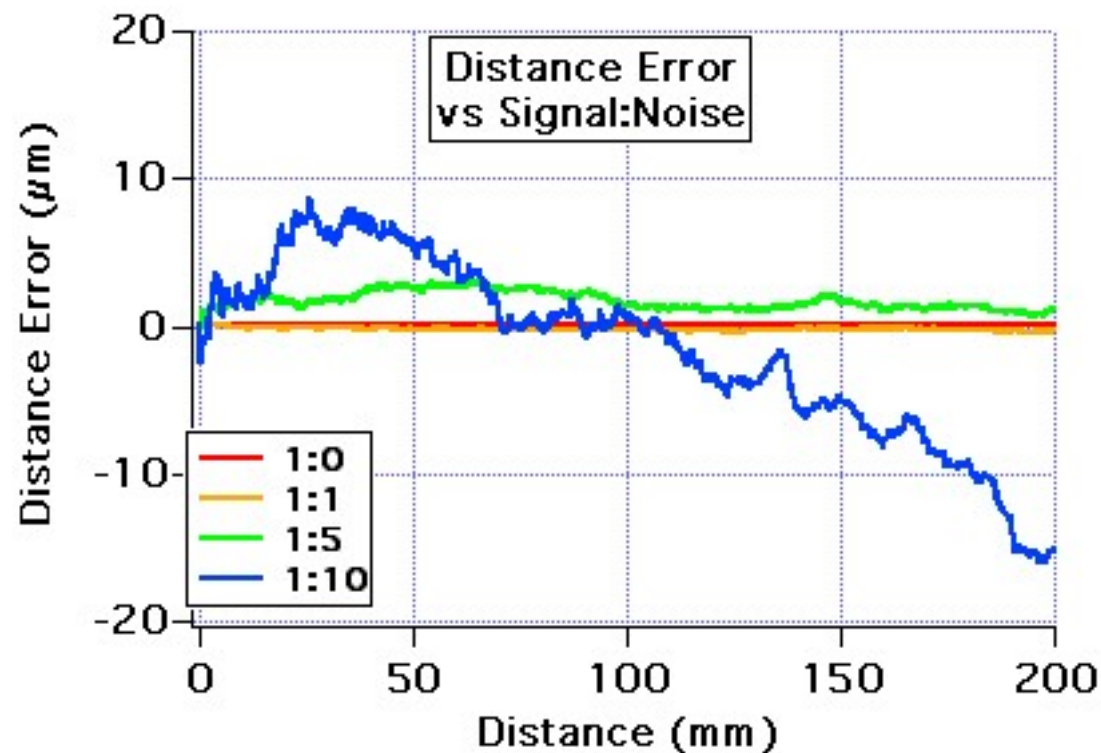
S/N = 1:10



# Study the Distance Uncertainty vs Random Noise on the Beat Waveform



Result: S/N = 1:10 gives  $< 20 \mu\text{m}$  error  
S/N = 1:1 almost no change in error

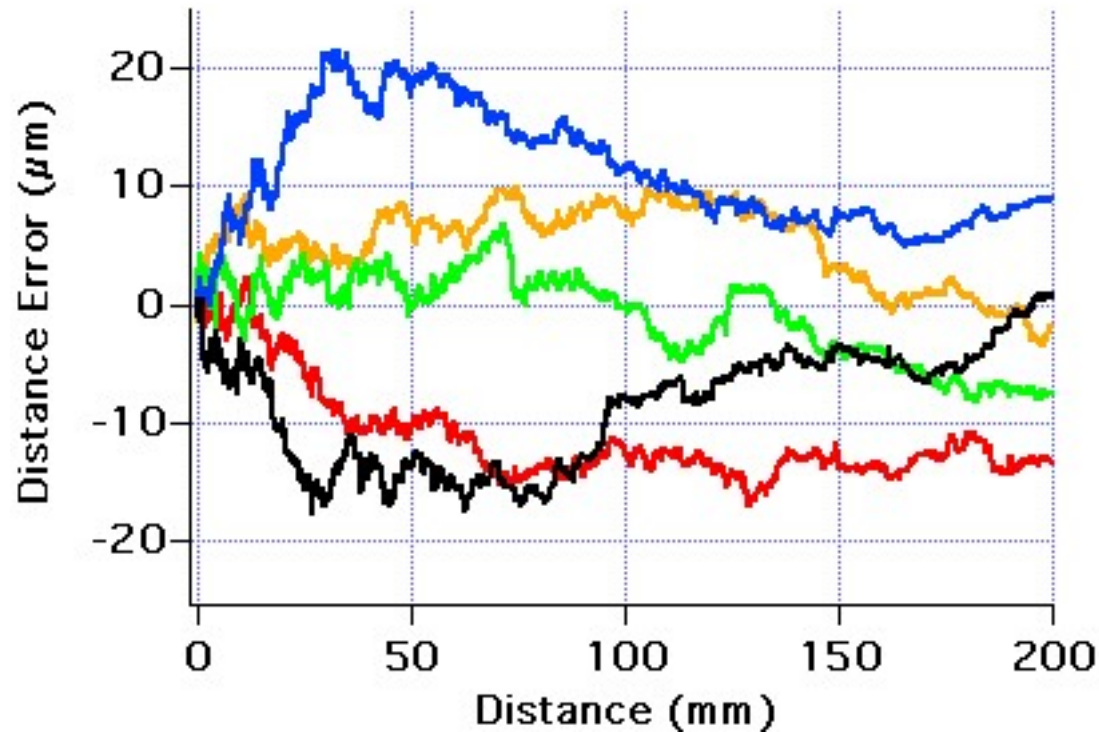


S/N = 1:10  
might be  
a problem--  
re-run several  
more times

Re-run five more cases with  $S/N = 1:10$



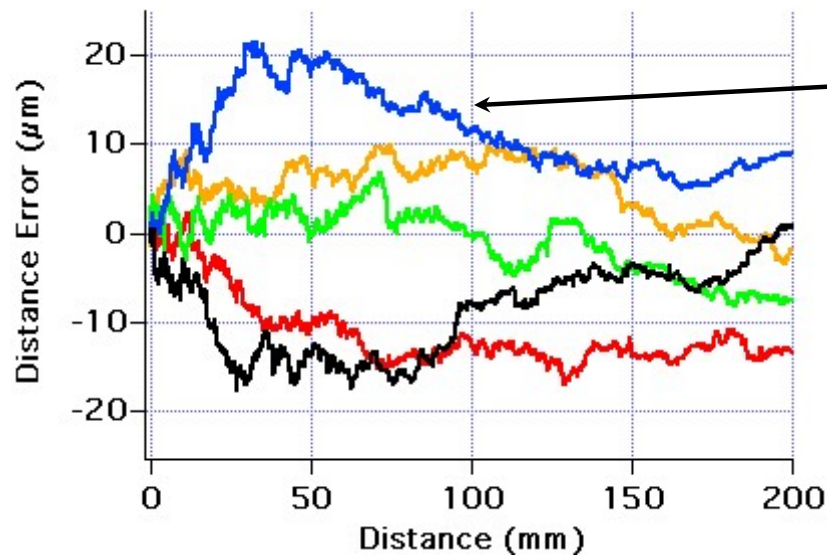
Result: Cannot guarantee  $< 10 \mu\text{m}$  uncertainty with  $S/N = 1:10$



try one  
more thing-->



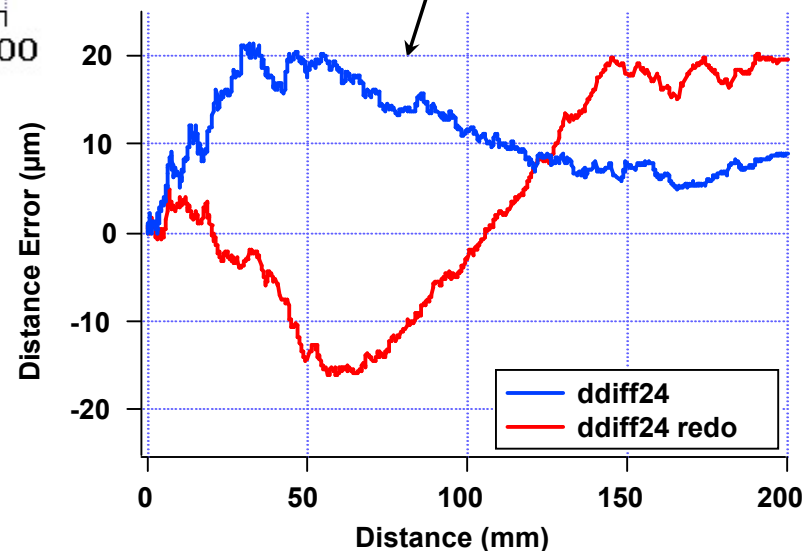
# Look more closely at the noise levels in the spectrograms



try tighter polygon extraction on blue curve

Result is not much better...

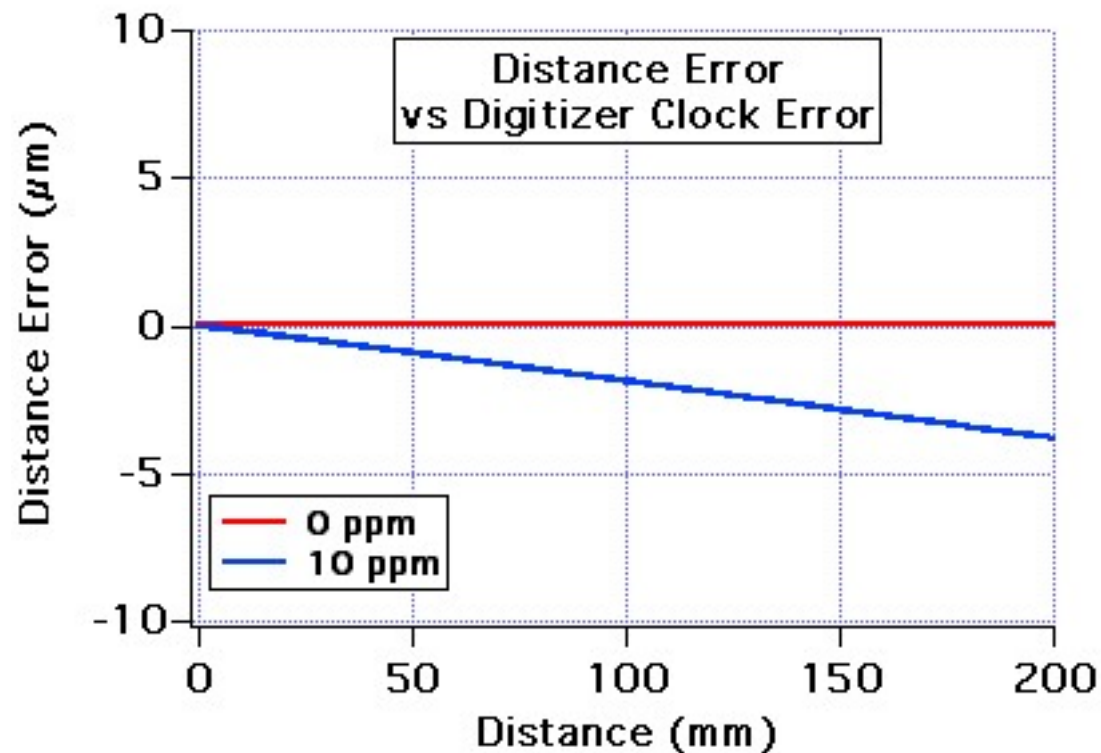
Result: cannot guarantee  $< 10 \mu\text{m}$  uncertainty with S/N = 1:10



# Study the Distance Uncertainty vs Digitizer Clock Error



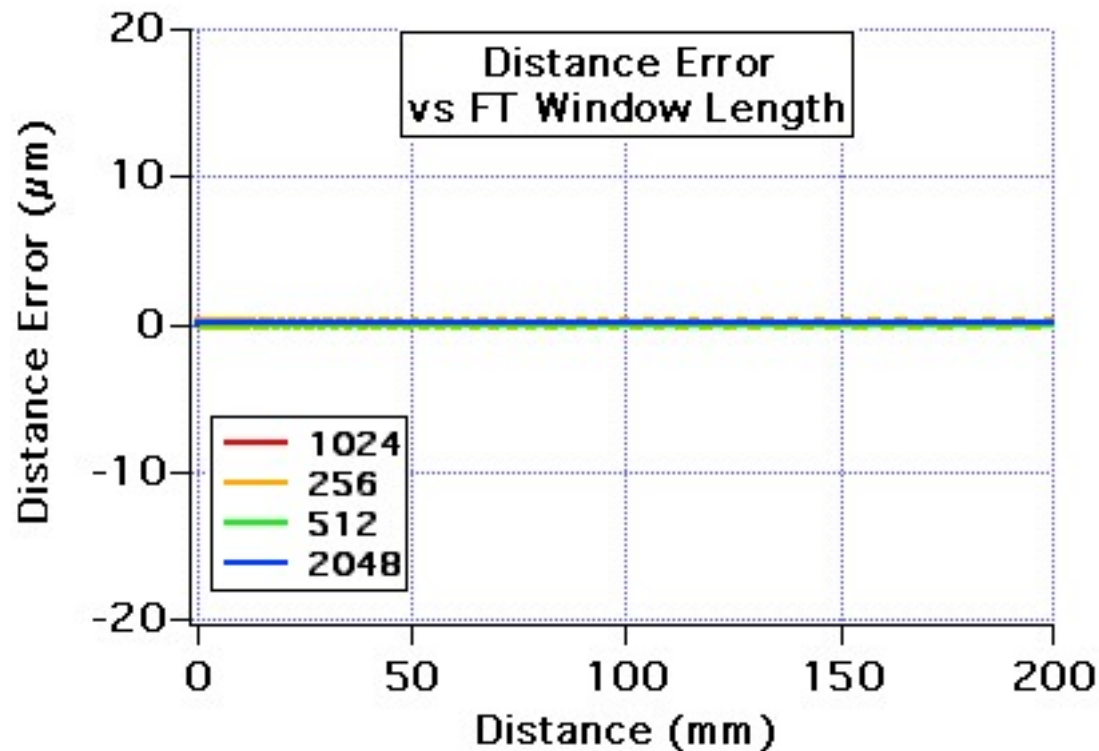
Result: Effect of 10 ppm error in digitizer sample time  
Note: digitizer spec is  $\pm 1.5$  ppm--very small



# Study the Distance Uncertainty vs FT Window Length



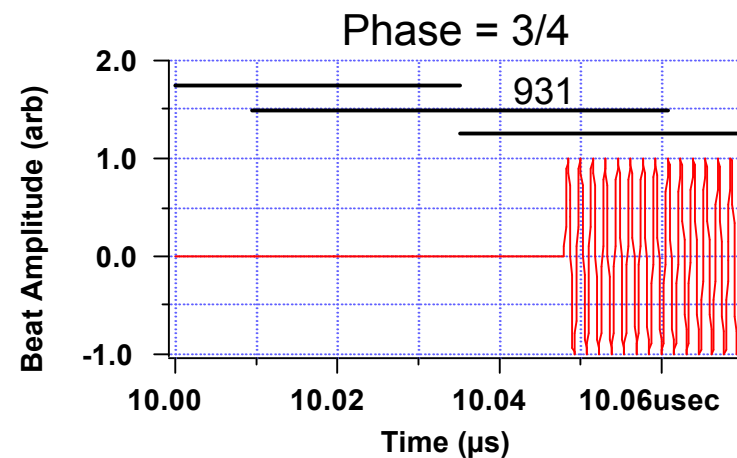
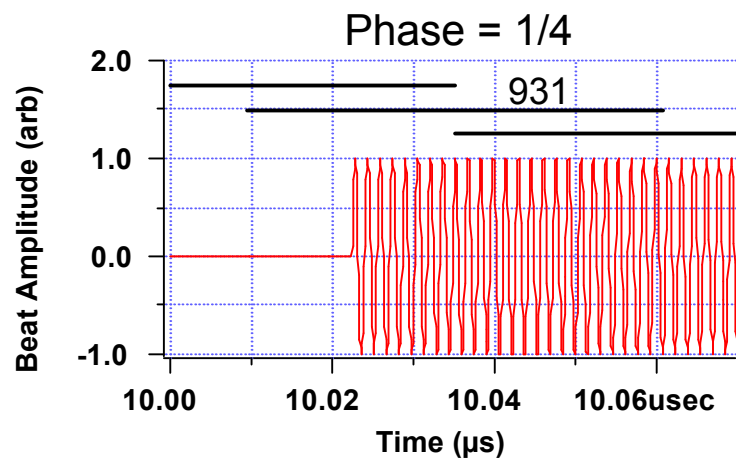
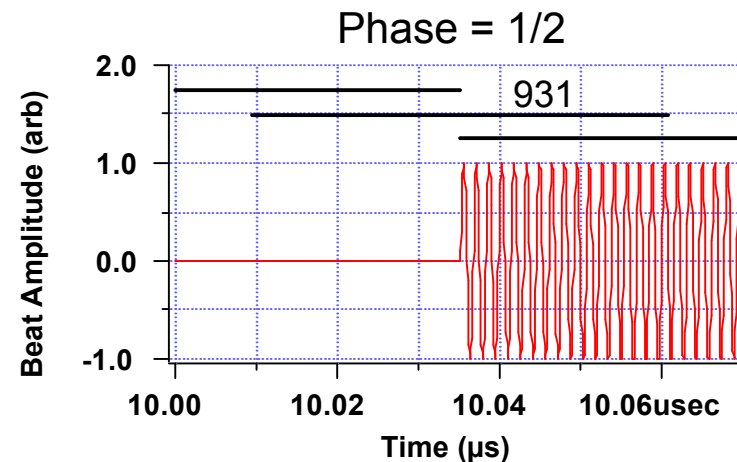
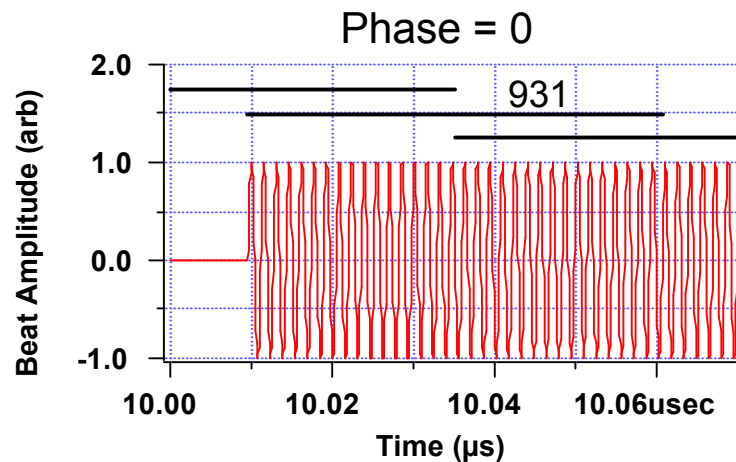
Result: no degradation in error with FT window length



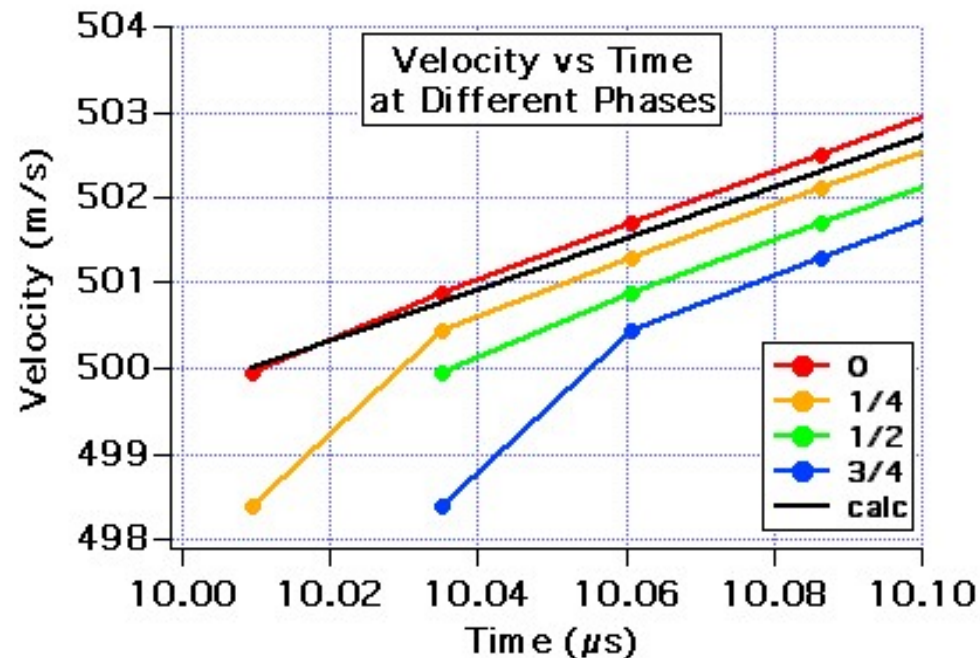
Note: need good S/N to be able to use 256 points = 13 ns FT windows



Study whether there is any effect that depends upon where the signal starts in the FT window



Study whether there is any effect that depends upon where the signal starts in the FT window

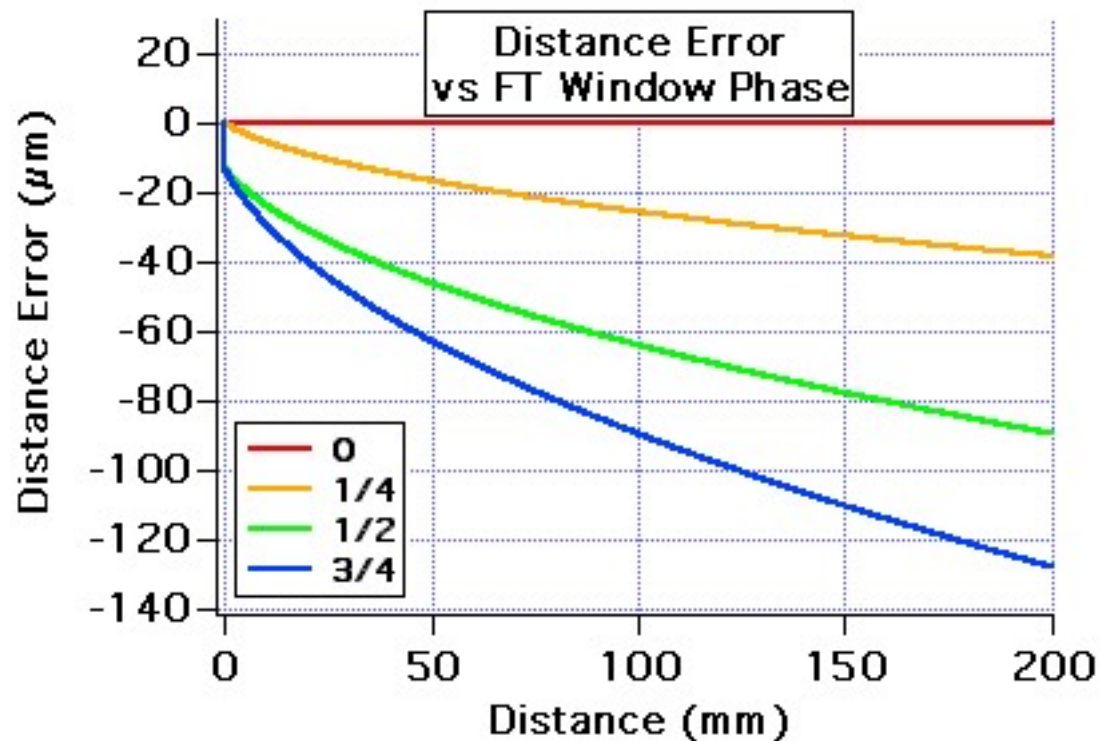


- 1) No data for phase = 1/2 or 3/4.
- 2) Calculated velocity is low by 1 m/s at phase = 3/4.

# Study the Distance Uncertainty vs Phase



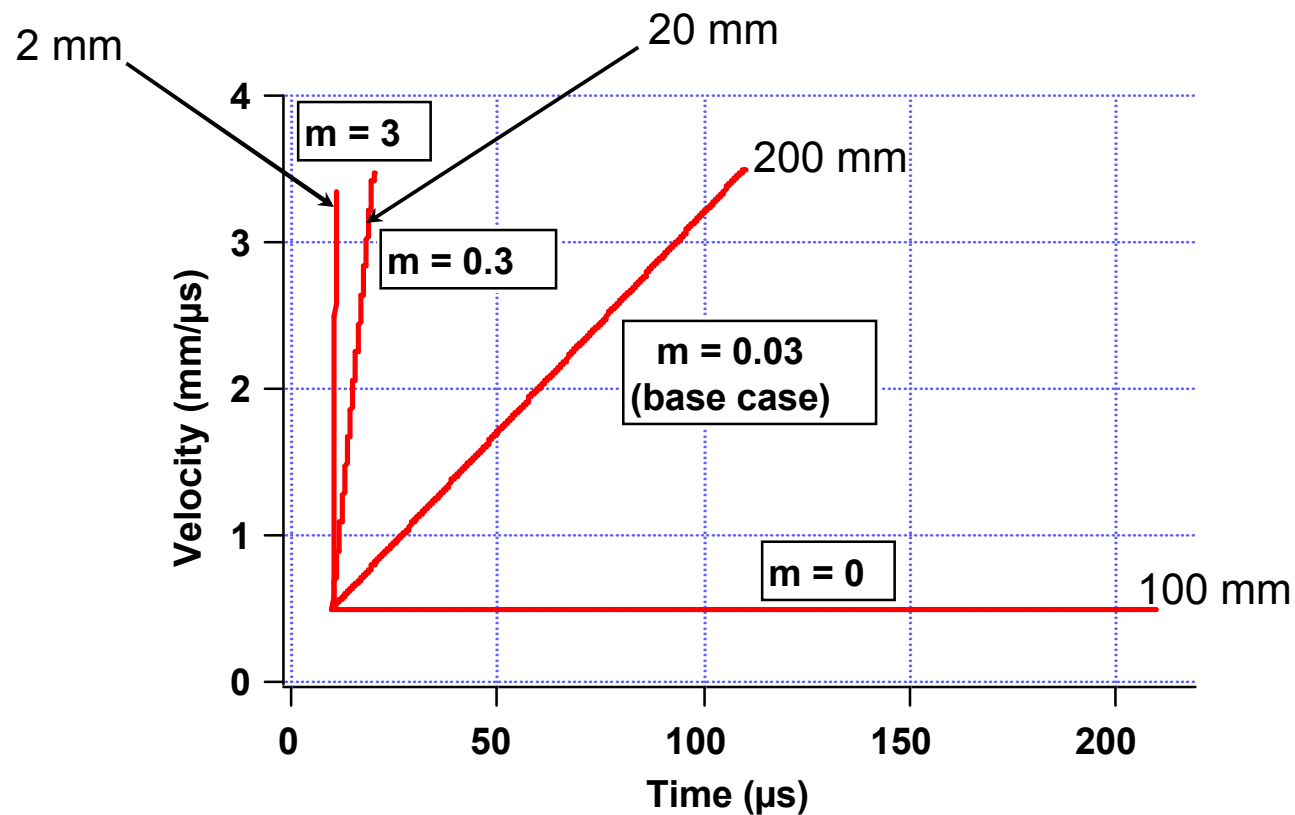
Result: need to make sure the beat waveform starts at the beginning of a Fourier transform window



# Study the Distance Uncertainty vs Acceleration



Vary acceleration by factor of 100, plus no acceleration

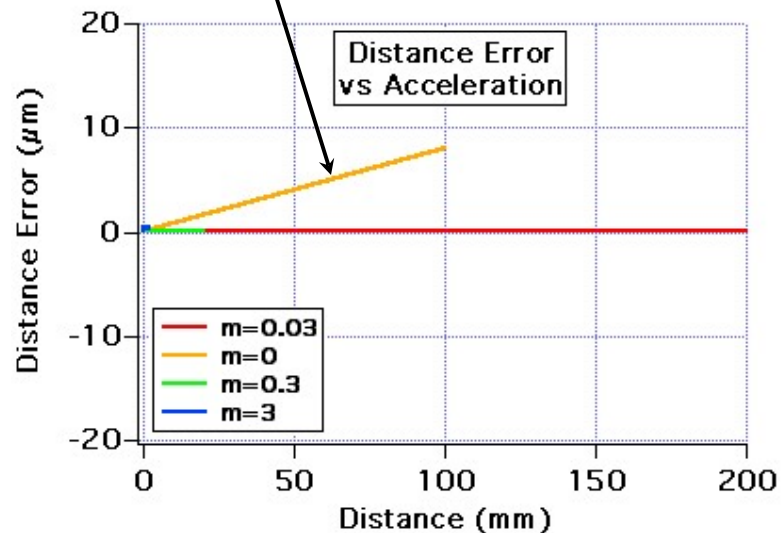


# Study the Distance Uncertainty vs Acceleration

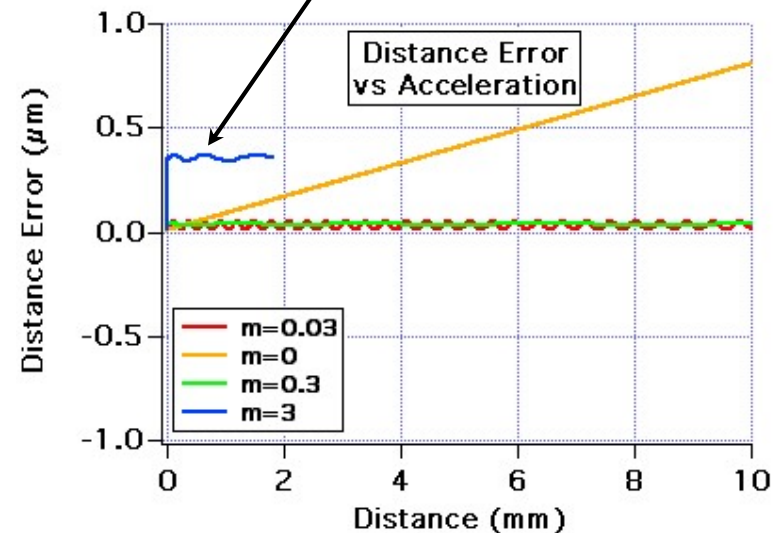


Interesting result: no acceleration is worse than acceleration

Note: processed  $v = 500.04$  m/s  
--> 0.008% error adds up



1st point  $v = 525.7$  m/s  
for  $m = 3$  case



Maybe continue study with accelerations approaching zero.

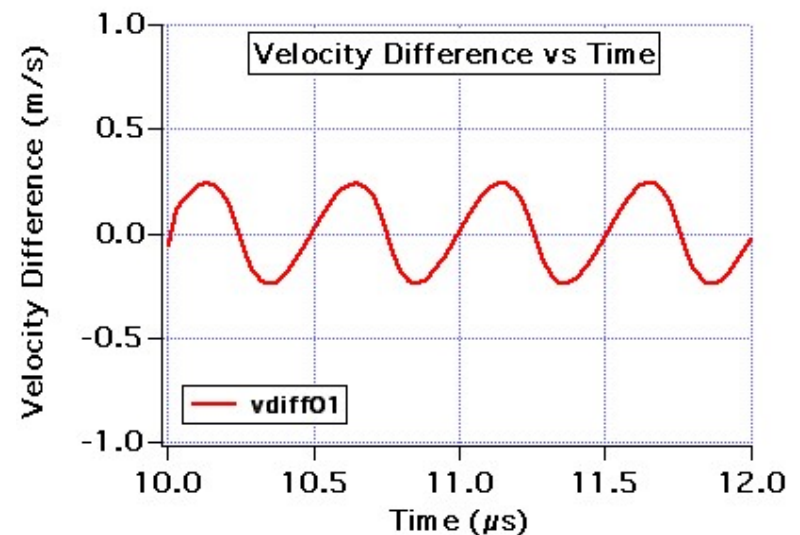
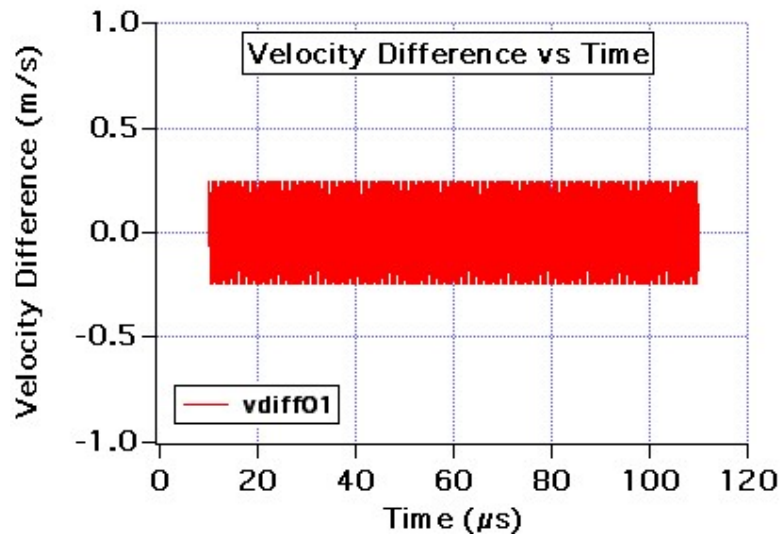
# Unexpected result: the code results have oscillatory velocity profiles



The amplitude for the base case is 0.2 m/s, but does not affect the integral (distance).

This effect is too small to be a concern for nearly all experiments that I do.

Artifact of MatLab routine?



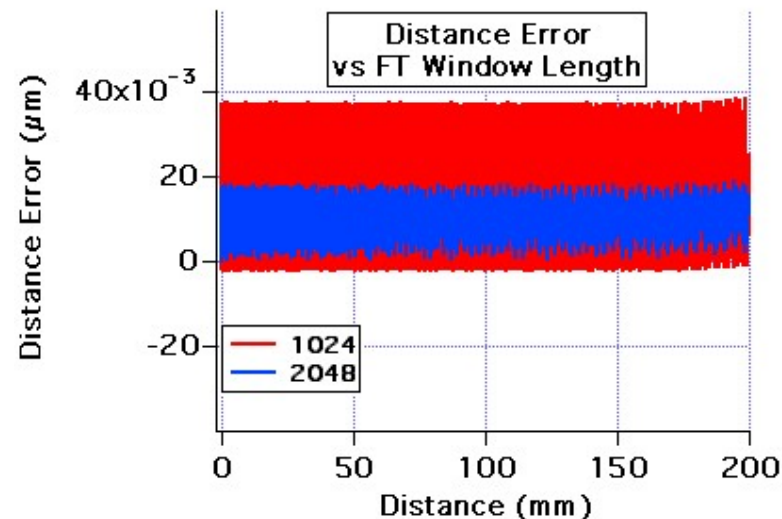
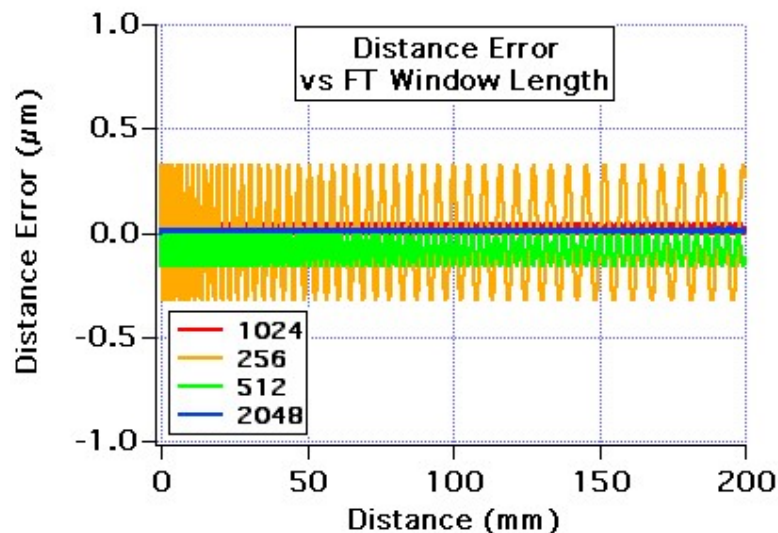
# Unexpected result: the code results have oscillatory velocity profiles



Look more closely at the FT window study

The amplitude of the oscillation decreases with increasing FT window length

FT window	Error (nm)
256	300
512	50
1024	20
2048	10



I have not taken the time to look into this--any ideas?

# Summary of distance uncertainties vs various parameters



1. Need  $< 0.1$  nm uncertainty in laser wavelength--not a problem
2. Cannot guarantee  $< 10$   $\mu\text{m}$  uncertainty with  $\text{S/N} = 1:10$
3. Digitizer sample rate uncertainty of 1.5 ppm is not a problem
4. FT window length does not impact the distance uncertainty
5. Need to make sure that beat waveform starts at the beginning of a FT window
6. Positive constant acceleration is not a problem, but zero acceleration has small effect

And unexpected result--velocities have very small amplitude oscillations

This does not appear to have an adverse effect on our data analysis